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Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics

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ABSTRACT

The use of semi-transparent BIPV as a form of on-site renewable energy generation in energy efficient sustainable buildings is increasing. Its popularity is due to its contribution towards zero-(or even plus) energy buildings. In urban cities where the buildings have limited rooftop area but large façade areas, adopting semi-transparent BIPV windows is an alternative for conventional windows. The semi-transparent BIPV windows not only solely generate electricity but also affect the buildings′ electricity usage through daylighting and heat gain/loss. In tropical climates where it is hot and humid all year round, the importance of window façade elements is even more pertinent due to high cooling load from the solar heat gains.

This paper examines the life cycle environmental and economic performance of commercially available semi-transparent BIPV modules for window application under the tropical conditions of Singapore. Energy simulations, previously performed, were adopted to conduct a life cycle assessment to determine the long term performance in terms of energy and carbon emissions, as well as cost considerations. The EPBT and EROEI for the modules ranged from 0.68 to 1.98 and 11.72 to 34.49 respectively. After considering government subsidies, some modules cost lower than conventional windows, while half of the remaining modules, achieved payback periods of 1.1–13.1 years. These performance indicators were used to form a decision-making tool to assist architects and building designers in the selection of BIPV modules for windows during the early design stages.
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Contents

Abbreviations: BIPV, building-integrated photovoltaic; CdTe, cadium telluride; CED, cumulative energy demand; CI(G)S, copper indium gallium selenide; EPBT, energy payback time; EROEI, energy returned on energy invested; GHG, greenhouse gas; LCA, life cycle assessment; mono-Si, mono-crystalline silicon; multi-Si, multi-crystalline silicon; NEB, net electricity benefit; SVF, sky view factor; VLT, visible light transmittance; WWR, window-to-wall ratio

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1. Introduction

The world energy consumption increased by almost 40% between 1990 and 2007, and is likely to continue to increase by another 8–10% every 5 years until 2035, partially due to population growth and rapid urbanisation/development in developing countries [1,2]. Globally, buildings represent 40% of primary energy usage and if energy consumed in manufacturing steel, cement, aluminium and glass used in construction is included, the number grows to more than 50% [3]. In Singapore, the building sector consumes about a third of her total electricity production [4]. To improve the performance of buildings, passive strategies such as energy efficient facades can be used. Improving façade elements′ energy performance is the key as they are the interface between the indoor and outdoor environments. The global agenda on reducing fossil fuel consumption has resulted in the push for adopting renewable technologies such as solar photovoltaic to generate clean energy. As such, building-integrated photovoltaic (BIPV) windows are considered one of the emerging glazing technologies for building façade elements [5,6].

When fully integrated with a building, BIPV is able to displace conventional building materials and generate electricity at the same time. As an integral element of the façade, semi-transparent BIPV windows not only affect the building′s energy efficiency through electricity generation but also via its thermal properties and daylight transmission. This multi-functional role of semi-transparent BIPV windows have been studied in terms of their application and combined energy saving potential in different climatic regions [7–10]. With such capabilities, semi-transparent BIPV′s design and application should be further investigated, especially its long-term implications due to its relatively high cost and long lifespan (typically 25 years). Such holistic evaluations are necessary especially in complicated cases such as this, as the performance that is intuitively anticipated may not be realised leading to greater impacts than those associated with conventional practices.

This paper considers the long-term energy generating potential of semi-transparent BIPV windows, adopting six different commercially available thin-film modules which may be used in Singapore office buildings. Using life cycle assessment (LCA), it evaluates the energy and emissions intensity of BIPV-generated electricity, net energy benefit, carbon emissions reduction and cost savings as well as energy, carbon emissions and costs payback associated with their integration in the facade. It presents a BIPV decision-making tool, developed to assist architects and building designers in making informed decisions about the choice of BIPV modules. Section 2 sets out the current literature pertaining to BIPV adoption, while issues related to the use of semi-transparent BIPV windows in Singapore office buildings, and their life cycle resource use are considered in Sections 3 and 4 respectively. Section 5 analyses the life cycle environmental performance of the BIPV modules while the economic aspects are being examined in Section 6. The development of the BIPV design tool is documented in Sections 7 and 8 concluding this paper.

2. Life cycle assessment of BIPV

Although photovoltaic technology is widely recognised as the cleanest power generating technology and therefore BIPV should also be encouraged, some argues that it consumes additional energy during its life cycle, particularly in the manufacturing processes, which may be larger than its energy output in its life time. Therefore, in order to thoroughly examine the life cycle performance of any photovoltaic system, an LCA which considers resource investment as well as output should be used to measure its sustainability.

The generic framework of LCA was established in 1997 under the guidelines set by the International Organisation for Standardisation [11,12]. To streamline the evaluation of photovoltaic technology, a set of guidelines explicitly drafted for LCA of photovoltaic systems, addressing the needs of photovoltaic professionals, was introduced recently. This guidance report published by the International Energy Agency (IEA) includes photovoltaic-specific parameters used as inputs in LCA, choices and assumptions in the life cycle inventory data analysis and modelling approaches [13]. These guidelines could be summarised into the following: (1) recommended technical specifications and characteristics of photovoltaic systems to be considered in LCA, (2) modelling approaches for photovoltaic system LCAs, and (3) guidance on reporting and communicating LCA results.

The recommended specific indicators are greenhouse gas emissions and (GHG) and cumulative energy demand (CED). GHG emissions during the life cycle stages of photovoltaic systems are estimated as an equivalent of CO_2 (denoted as $kgCO_2eq$) using an integrated 100-year time horizon from the global warming potential factors published by the Intergovernmental Panel on Climate Change (IPCC) [14]. The CED describes the consumption of fossil, nuclear and renewable energy sources along the life cycle of a good or service. The energy sources in the CED indicator result include fossil, nuclear, biomass, hydro, primary forest, wind and solar. The impact indicators can be further processed into GHG emissions intensity of photovoltaic electricity, energy payback time (EPBT) and energy return on energy investment (EROEI). EPBT, measured in years, can be calculated relative to the average grid electricity currently used in any country. EROEI, expressed as energy generation per unit of energy input, denotes the units of energy for each unit invested in the production process.

There have been many LCA studies on photovoltaic systems. In a recent LCA review of five common photovoltaic system technologies (mono-Si, multi-Si, a-Si, CdTe thin-film and CIGS thin-film), Peng et al. [15] discussed them in terms of energy requirement, energy payback time (EPBT) and greenhouse gas (GHG) emission rate during whole life cycle. It was concluded that mono-Si photovoltaic system demonstrates the worst environmental performance due to its high energy intensity during the manufacturing and production processes. It was also determined that in general, the EPBT of mono-Si photovoltaic systems ranged from 1.7 to 2.7 years with GHG emission rate between 29 and 45 gCO_2eq/kWh. The EPBT and GHG emission rates of thin-film photovoltaic systems were within 0.75–3.5 years and 10.5–50 gCO_2eq/kWh, respectively. This finding encourages the adoption of semi-transparent BIPV as mono-Si

photovoltaic modules are opaque in nature whereas thin-film technology allows the modules to be semi-transparent.

In a study of roof-mounted BIPV in the UK, Hammond et al. [16] used an integrated approach to evaluate the environmental and economic feasibility of a 2.1 kWp system, with mono-Si modules. He estimated the EPBT to be 4.5 years with an EROEI of 4.6 considering a 25 years BIPV system lifetime. The study also estimated a carbon payback period of 4 years and a "carbon gain ratio" of 5:1. However, the prevailing market conditions were not conducive for BIPV system to break even in economic terms, which clearly demonstrated the importance of government support schemes to promote uptake of BIPV in the UK. In the US, Keoleian and Lewis [17] evaluated BIPV energy and environmental performance relative to conventional grid electricity and building materials. They concluded that for a 2 kWp roof-mounted BIPV installation using thin-film modules, the EPBTs are between 3.39 and 5.52 years for 15 selected cities. They also observed shorter EPBT values for cities with higher insolation.

In sub-tropical Hong Kong, a 22 kWp roof-mounted BIPV system with mono-Si modules was analysed in terms of energy and emissions payback time [18]. The results showed that the EPBT of the BIPV system was 7.3 years and the GHG payback time was 5.2 years, with respect to fuel mix of local power stations. The research further extended to discuss the EPBTs for different orientations, ranging from 7.1 years (optimal orientation) to 20.0 years for a west-facing vertical BIPV façade. Lim et al. [19] performed a study on the environmental benefits and technical impacts of installing roof-mounted BIPV systems in Malaysia. Using a 1 kWp BIPV system with three different PV technologies (mono-Si, multi-Si and thin-film), he examined the energy performance and implications of installing at various locations in Malaysia. He estimated that the EPBT values were 3.2–4.4, 2.2–3.0 and 1.9–2.6 years for mono-Si, multi-Si and thin-film modules, respectively. It was also highlighted that the high embodied energy of Malaysian BIPV systems were due to the logistics of importing components which also resulted in higher costs.

A couple of studies have considered façade integration of BIPV with different technologies. Oliver and Jackson [20] examined the energy costs of supplying electricity in Europe and included the use of an avoided cost technique to illustrate the benefit of adopting BIPVs. The façade mounted multi-Si modules were estimated to require 2.9 MJ/kWh as embodied energy. The EPBT and EROEI were 5.5 years and 4.5 respectively. When the embodied energy of the conventional glass cladding system was deducted from the BIPV as an avoided burden, the BIPV net embodied energy value was reduced to 2.6 MJ/kWh. With the net BIPV embodied energy, the EPBT was reduced to 4.8 years while EROEI increased to 5.2.

In the US, Perez and Fthenakis [21] investigated the actual performance of a 11.3 kWp BIPV mono-Si façade system and its environmental footprint was extrapolated to other façade systems by means of performance ratio and avoided building materials. They reported the system′s EPBT and EROEI to be 3.81 years and 7.2 respectively. The GHG emissions rate was 60.5 gCO_2eq/kWh.

However, LCA research that considers the multi-functional performance of semi-transparent BIPV facades (against traditional double-glazed windows) in tropical regions is lacking. In the hot and humid climate of tropics, high insolation received through the semi-transparent façade affects the building′s interior lighting and solar heat gain in addition to the electricity generated by the photovoltaic. If the savings in building materials (BIPV modules replacing building envelope materials) and building space conditioning loads due to BIPV integration are taken into account, the life cycle performance could reveal higher potential [18]. It is also imperative to examine the effects of transporting photovoltaic modules to countries where they are not produced locally, such as Singapore. The information obtained from the LCA study will also provide the basis for the decision-making process when selecting from different BIPV modules for window façade applications.

3. Energy performance of semi-transparent BIPV windows in Singapore

For a holistic view, semi-transparent BIPV windows′ energy performance evaluations should include all energy-related impacts. Ng et al. [22] introduced a performance index to quantify the overall electrical benefit of semi-transparent BIPV windows. Termed as the "Net Electrical Benefit (NEB)" and as shown in Eq. (1), the elements included in its calculation are, photovoltaic electricity generation and electricity savings due to natural sunlight and the difference in cooling electricity.

$$NEB = L_{savings} - C_{electricity} + PV_{generation} \quad [kWh] \tag{1}$$

where L is the difference in artificial lighting savings through the utilisation of natural sunlight; C is the difference in electricity consumption required for space conditioning due to transmission of additional solar hear gain; and PV is the electricity generation output from photovoltaic window.

The characteristics of the six commercially-available thin-film modules that were adopted for this study are shown in Table 1. Their energy performance was estimated based on their integration as

Table 1
Technical data and specifications of six semi-transparent BIPV modules under investigation.

	Module 1	Module 2	Module 3	Module 4	Module 5	Module 6
Module area (mm × mm)	980 × 950	1300 × 1100	1300 × 1100	1300 × 1100	989 × 930	980 × 950
Efficiency [%]	8.02	5.90	3.32	4.43	5.01	4.75
SHGC	0.289	0.413	0.298	0.387	0.154	0.123
U-value [W/(m^2 K)]	5.08	4.80	5.08	5.10	1.67	2.14
Visible light transmittance [%]	9.17	5.19	1.84	4.17	6.91	7.34
Photovoltaic technology	a-Si	μc-Si	μc-Si	μc-Si	a-Si	a-Si
Construction assembly	Single-glazed laminate	Single-glazed laminate	Single-glazed laminate	Single-glazed laminate	Double glazed unit	Double glazed unit
Appearance	Standard	Red	Golden	Dark blue	Standard	Standard
City, Country of origin	Japan	Taiwan	Taiwan	Taiwan	Germany	Taiwan
Cost per module (SGD)	$754	$446	$446	$446	$1165	$1520
Weight (kg)	20	23	23	23	41	49
BOS efficiency	0.90					

Note: a-Si= amorphous silicon; and μc-Si=micromorph silicon.

Table 2
Annual energy performance as compared to double-glazed windows for the six investigated modules.

	Orientation	Lighting electricity savings [A] (kWh/yr)	Cooling electricity savings [B] (kWh/yr)	PV generation [C] (kWh/yr)	Annual NEB [A+B+C] (kWh/yr)
Module 1	East/West	−1218	3871	5297	7951
	North/South	−1364	3061	4511	6207
Module 2	East/West	−1862	2341	3897	4376
	North/South	−1981	1848	3318	3185
Module 3	East/West	−2464	3280	2193	3009
	North/South	−2508	2529	1867	1888
Module 4	East/West	−2043	2541	2926	3424
	North/South	−2140	1991	2491	2342
Module 5	East/West	−1622	6014	3309	7702
	North/South	−1773	4868	2817	5912
Module 6	East/West	−1547	6638	3138	8229
	North/South	−1703	5374	2671	6342

Note: results extracted and tabulated from Ng et al. [22].

semi-transparent BIPV windows in a highly-glazed Singapore office building with a WWR of 90%. The details of simulation and results were published in Ng et al. [22] and will not be discussed further here. However, a breakdown of the energy simulation results for the six modules across the four main orientations are tabulated in Table 2 for easy reference. As the energy performance of East and West (and North and South) are very similar due to the sky conditions in Singapore [23], they are averaged and presented together (i.e. as EW and NS). The modules being semi-transparent, artificial lighting requirement is increased relative to clear double-glazed windows used as the base case.

4. Life cycle resource use of semi-transparent BIPV windows in Singapore

The module's manufacturing phase resource uses were obtained from the *ecoinvent* (v2.1) database [24,25] and was modified to represent the actual scenario. Representative inverter and balance of system components were also selected from the same database. Singapore's national grid electricity mix which comes from natural gas (75.8%), fuel oil (21.6%), diesel oil (0.3%) and waste incineration (2.3%) [26] was considered for this study. With 2.5% transmission losses, the carbon emissions of Singapore's grid electricity are 601.0 gCO_2eq/kWh [27]. This highlights an added benefit of BIPV systems, which is avoiding transmission losses associated with the national electricity grid due to on-site electricity generation. All unit processes within the system boundary that are likely to make a material contribution (of more than 1%) have been included.

The LCA stages included were the manufacturing of BIPV components from raw materials, their transport from country of origin to the site in Singapore, installation on site, operation and maintenance, and disposal/recycling of waste. The following assumptions were used for the life cycle inventory.

4.1. Manufacturing of BIPV

Manufacturing data were derived from two data sources [25,28]. The manufacturing processes in *ecoinvent* database did not have primary data on μc-Si module technology. Therefore, for modules 2, 3 and 4 which use μc-Si technology, secondary data were adopted. The manufacturing data thus obtained were modified to reflect the country specific electricity mix used during the manufacturing process based on country of origin for respective modules. The electricity mix for Japan and Germany were obtained from *ecoinvent* and Taiwan's electricity mix was retrieved from a secondary source [29]. The additional materials required to manufacture modules 5 and 6, which are double-glazed, were also included. The weight of the modules is shown in Table 1. In addition, two inverters of 2.5 kW each were also included. The total weight of the inverters is 39 kg (18.5 kg each).

4.2. Transport to site

Since BIPV modules and inverters were imported to Singapore, transport from overseas port to site in Singapore was included. Data were unavailable to estimate the land transport distance and mode in the country of origin and therefore this was omitted. Transoceanic freight shipping was assumed to deliver the components from overseas port to the port in Singapore, with onward transport to the site by courier. The distances between ports were obtained from an online shipping distance calculator [30] and the courier distance was assumed to be 20 km (site assumed to be at the centre of Singapore).

4.3. Installation on site

Besides the inverter, the remaining balance of system included the façade installation, mounting energy use and electric installation (cabling, trunking, etc.) in Singapore. These data were obtained from *ecoinvent* and modified with Singapore's grid electricity mix.

4.4. Operation and maintenance

The lifetime of the module was assumed to be 25 years. This was the warranty provided by the manufacturers and is also in accordance with the IEA [13] recommended life expectancy. The degradation of the module over time reduces the module electricity conversion efficiency. Therefore, a linear degradation reaching 80% of the initial efficiency at the end of the lifetime was used. The inverter life was assumed to be 15 years and therefore, one replacement with an identical inverter during the BIPV system life time was included. Other replacement parts were considered as negligible and therefore disregarded in the calculation.

4.5. Decommissioning, disposal and recycling of waste

The BIPV modules and components contain glass, aluminium and semiconductor materials that can be successfully recovered and reused, either in new modules or other products. There have been recent suggestions on methods for end-of-life recovery of these materials [31,32]. However there is still a lack of reliable scientific or empirical data and established recycling strategies [16,18,19,33–35], as such modules were considered to be disposed as municipal solid waste in Singapore. The aluminium façade mountings were however, assumed to be recycled for future use.

5. Life cycle environmental performance of semi-transparent BIPV windows in Singapore

The life cycle emissions and embodied energy of the individual components of the BIPV system, the six PV modules and conventional double glazed windows are presented in Table 3. The results indicate that the environmental burden associated with installing BIPV modules is significantly reduced if we deduct the avoided burden of double-glazed windows, which are currently the standard for energy efficient tropical buildings. For module 1, the GHG emissions are −951 $kgCO_2eq$ which implies that installing a BIPV

façade incorporating module 1 results in even lesser emissions than double-glazed windows. The remaining modules have GHG emissions of between 573 and 1647 $kgCO_2eq$.

For the cumulative energy demand, the six systems require energy of 29–106 GJ. Fig. 1 presents life cycle energy use at different life stages for the BIPV facade systems for the six investigated modules. It can be seen that the photovoltaic manufacturing process and the balance of systems makes up the largest contribution for all modules. In the case of module five, in addition to the above, transportation energy use is also significant, due to the need for cross-continental shipping as the module is imported from Germany.

5.1. Energy and emissions intensity of PV generated electricity

The energy and GHG emissions intensities of electricity generated by the facade systems incorporating these modules facing different orientations are illustrated in Fig. 2. Module 1 performs the best with the lowest energy and emissions intensities, at 240–310 MJ/kWh and −5 gCO_2eq/kWh respectively. The double-glazed modules (5 and 6) were the next, in terms of performance, with GHG emissions of 45–62 gCO_2eq/kWh and energy intensities of 823–1265 MJ/kWh. The worst-performing modules were the coloured-tinted modules. Their GHG emissions and energy intensities were 98–212 gCO_2eq/kWh and 1369–2754 MJ/kWh, respectively. This is mainly due to their low visible transmittances, energy efficiencies and higher thermal conductivities.

Table 3
Life cycle energy and GHG emissions from BIPV assembly over 25 years for the six semi-transparent BIPV modules under investigation.

	GHG emissions ($kgCO_2eq$)	Cumulative energy demand (GJ)
(a) BIPV module construction		
Module 1	3231	68.6
Module 2	5779	71.5
Module 3	5139	53.2
Module 4	5411	61.0
Module 5	4744	87.5
Module 6	4897	128.6
(b) Integrated façade construction	3239	51.9
(c) Module installation	2	0.03
(d) Electrical system installation	219	2.9
(e) Inverter (including replacement)	728	13.1
(f) Double-glazed Window	8369	90.6
Net total [(a)+(b)+(c)+(d)+(e)-(f)]		
Module 1	−951	45.7
Module 2	1647	49.3
Module 3	894	29.5
Module 4	1215	37.9
Module 5	573	64.7
Module 6	755	106.2

Note: values may not add up due to rounding.

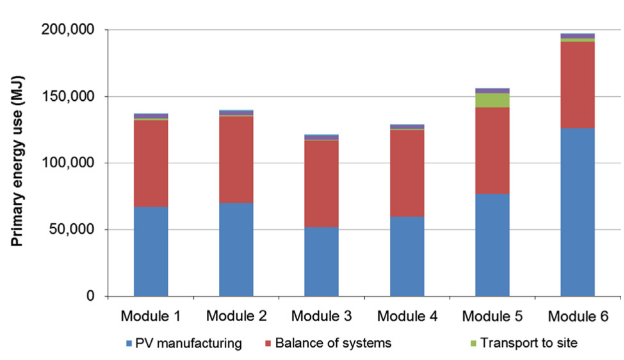

Fig. 1. Life cycle energy use at different life stages for the six BIPV façade systems.

5.2. EPBT and EROEI investigations

The six modules have a net electricity benefit (NEB) of 42,538–197,897 kWh relative to double-glazed windows and consume 29,461–106,234 MJ more primary energy over its 25-year lifetime (see Table 3). At the annual NEB rate of 1888–8229 kWh/year, the EPBT and EROEI of the modules are tabulated and shown in Table 4. In terms of EPBT, EW orientations perform better than NS for all modules. The EPBT values range from 0.68 to 1.52 for EW and 0.87 to 1.98 for NS orientations, with module 1 the lowest (0.68–0.97) and module 6 the highest (1.52–1.98). For EROEI, the values range from 11.72 to 34.49. Module 1 has the highest EROEI (26.75–34.39), while module 6 obtained the lowest values (12.13–15.81).

The results obtained generally perform better than the previous studies which provided EPBTs of 1.8–3.5 with an average of 2.73. This is largely due to the discounting of conventional glass façade's embodied energy from the BIPV systems embodied energy.

5.3. Sensitivity of results

In order to test the sensitivity of life cycle performance results to the assumptions used, a sensitivity analysis is conducted with variations to the base case scenario. The six scenarios selected are

- Scenario 1: Module 5 is manufactured in Asia, instead of Europe. It is assumed to be manufactured in southern China. Chinese energy mix is used for manufacturing with respective transport requirements.

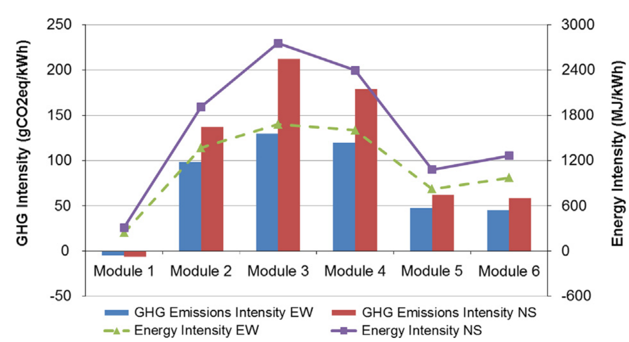

Fig. 2. Energy and GHG emissions intensities of electricity generated by the façade systems incorporating BIPV modules for different orientations.

Table 4
EPBT and EROEI of various orientations and the six investigated modules.

	EPBT (years)		EROEI	
	EW	NS	EW	NS
Module 1	0.68	0.87	34.49	26.75
Module 2	1.33	1.83	17.17	12.29
Module 3	1.15	1.85	20.09	12.25
Module 4	1.31	1.91	17.54	11.72
Module 5	0.99	1.29	24.16	18.45
Module 6	1.52	1.98	15.81	12.13

Note: for EPBT and EROEI definition, refer to chapter 2 paragraph 3.

- Scenario 2: Modules 1–6 are manufactured in Singapore. Hence, cross-continental transport is eliminated and Singapore′s electricity mix is used.
- Scenario 3: Shading due to nearby buildings in the urban context that lower the solar incident on the façade windows. Unobstructed window has Sky View Factor (SVF) of 50%, and reductions of the SVF by 1/3 and 2/3 to obtain 33.3% and 16.7% respectively are considered.
- Scenario 4: Modules manufactured in Singapore are used in buildings with 33.3% and 16.7% SVF.

The environmental performance results in terms of GHG emissions and CED of the sensitivity analysis are shown in Tables 5 and 6. The embodied energy for scenarios 3 and 4 will equal to that of base case and scenario 2, respectively and hence are not shown. Life cycle energy use for scenario 1 indicates a 15% decrease, when cross-continental freight is reduced to shipping within the continent and China′s electricity mix is used instead.

Table 5
Comparison of the six semi-transparent BIPV modules′ life cycle CED under different scenarios.

Cumulative Energy Demand (GJ)						
	Module 1	Module 2	Module 3	Module 4	Module 5	Module 6
Base case	45.7	49.3	29.5	37.9	64.7	106.2
Scenario 1	–	–	–	–	55.1	–
Scenario 2	29.3	22.1	13.9	17.4	36.5	86.2

Note: for CED definition, refer to chapter 2 paragraph 3.

Table 6
Comparison of the six semi-transparent BIPV modules′ life cycle GHG emissions under different scenarios.

GHG emissions ($kgCO_2eq$)						
	Module 1	Module 2	Module 3	Module 4	Module 5	Module 6
Base case	−951	1647	894	1215	573	755
Scenario 1	–	–	–	–	2025	–
Scenario 2	−869	1228	640	890	−753	−58

Note: for GHG emissions definition, refer to chapter 2 paragraph 3.

For scenario 2, with all modules made in Singapore (eliminating freight and adopting Singapore′s electricity mix), the life cycle energy decreases significantly for all modules, ranging from 19% to 55% of the base case. However, the life cycle GHG emissions for scenario 1 are 253% higher than the base case scenario. For scenario 2, all modules indicate a reduction of 25–231% except for module 1, which has an increase of 9%. The consistent decrease in the life cycle energy compared to the mixed results for the GHG emissions show that while reducing the transport by manufacturing in a closer country has a major impact on reducing CED, it might increase the GHG emissions due to the electricity mix used in the country of manufacture. In the sensitivity analysis considered here, the increase in GHG emissions is due to Singapore′s and China′s electricity mix having a GHG emissions rate of 0.601 $kgCO_2eq/kWh$ (compared to Japan′s rate of 0.556 $kgCO_2eq/kWh$) and 1.170 $kgCO_2eq/kWh$ (compared to Germany′s rate of 0.656 $kgCO_2eq/kWh$) respectively.

The EPBT and EROEI for the different scenarios derived based on their respective life cycle energy use are shown in Table 7. For scenario 1, where module 5 is manufactured in Asia, the EPBT improved to 0.84 and 1.10 years, along with moderately higher EROEI of 28.37 and 21.67 for east/west and north/south orientations, respectively. This translates to a 15% decrease in EPBT and 17% increase in EROEI as compared to the base case. For scenario 2, EPBT for various modules and orientations decreases while the EROEI increases as expected from the lower CEDs. The EPBT ranges from 0.43 to 1.60 years while the EROEI ranges from 14.96 to 53.81.

For scenario 3, where the windows SVF are reduced by 1/3 (SVF of 33.3%), the EPBTs are 1.4–12.39 years (increase of 105–526%) and the EROEIs are 1.54–16.24 (decrease of 53–87%). When the SVF is further decreased in order to obstruct 2/3 of a window (SVF of 16.7%), both modules 3 and 4 do not pay back within its lifetime for all orientations. Module 2 achieves pay back when facing north/south orientations but not east/west orientations. The EPBTs obtained are 3.82–21.35 years (an increase of 462–978%). The EROEI for those that can pay back ranged from 1.08 to 5.76, signalling a decrease of 83–91%.

For scenario 4, where locally manufactured modules were investigated with 1/3 reduction in SVF all modules still achieve energy breakeven during the lifetime. The EPBTs are between 0.9 and 5.14 years (an increase of 32–160%) and EROEI of 3.26–25.33 which equates to a reduction of between 27% and 72%. When the obstruction was increased to 2/3 of window area (SVF of

Table 7
EPBT and EROEI of the six semi-transparent BIPV under different scenarios.

		Base case		Scenario 1		Scenario 2		Scenario 3				Scenario 4			
								33.3% SVF		16.7% SVF		33.3% SVF		16.7% SVF	
		EPBT	EROEI	EPBT	EROEI	EPBT	EROEI	EPBT	EROEI	EPBT	EROEI	EPBT	EROEI	EPBT	EROEI
Module 1	E/W	0.68	34.49	–	–	0.43	53.81	1.40	16.24	4.74	4.59	0.90	25.33	3.00	7.17
	N/S	0.87	26.75	–	–	0.56	41.73	1.94	11.50	3.82	5.76	1.24	17.95	2.43	8.98
Module 2	E/W	1.33	17.17	–	–	0.60	38.23	3.53	6.09	#N/A	0.24	1.56	13.56	#N/A	0.53
	N/S	1.83	12.29	–	–	0.82	27.36	6.31	3.20	21.35	1.08	2.74	7.13	7.36	2.40
Module 3	E/W	1.15	20.09	–	–	0.54	42.56	3.32	6.58	#N/A	−1.73	1.55	13.94	#N/A	−3.65
	N/S	1.85	12.25	–	–	0.87	25.96	12.39	1.54	#N/A	−0.64	5.14	3.26	#N/A	–1.36
Module 4	E/W	1.31	17.54	–	–	0.60	38.24	4.12	5.12	#N/A	−1.14	1.86	11.17	#N/A	−2.49
	N/S	1.91	11.72	–	–	0.87	25.56	11.79	1.60	#N/A	−0.21	4.78	3.48	#N/A	−0.45
Module 5	E/W	0.99	24.16	0.84	28.37	0.56	42.82	1.99	11.85	6.93	3.34	1.12	21.01	3.86	5.92
	N/S	1.29	18.45	1.10	21.67	0.73	32.71	2.77	8.43	5.55	4.19	1.56	14.95	3.10	7.42
Module 6	E/W	1.52	15.81	–	–	1.23	19.49	3.03	7.88	10.41	2.28	2.45	9.72	8.38	2.81
	N/S	1.98	12.13	–	–	1.60	14.96	4.18	5.67	8.46	2.80	3.38	6.99	6.82	3.45

#N/A – BIPV system does not break even.

Table 8
Cost of supply of glazing, aluminium framing and installation of single and double-glazed windows.

	Single Glazed (SGD)			Double glazed window (SGD)		
	Supply of glazing	Supply of alum. framing	Installation	Supply of glazing	Supply of alum. framing	Installation
Company 1	60.00	270.00	70.00	130.00	350.00	120.00
Company 2	50.00	250.00	80.00	120.00	280.00	100.00
Company 3	32.10	107.00	53.50	128.40	128.40	64.20
Average (m^2) (nearest dollar)	**47.00**	**209.00**	**68.00**	**126.00**	**253.00**	**95.00**
Total (81 m^2) (nearest dollar)	**3837**	**16,929**	**5495**	**10,217**	**20,477**	**7673**

All prices are inclusive of 7% goods and service tax.

Table 9
Total costs and breakdowns of the six investigated semi-transparent BIPV systems and double-glazed windows.

	PV Module (81 m^2)	Glazing contractors' installation (81 m^2)	PV System Integrator's electrical and BOS (81 m^2)	Total Cost (81m^2)
Module 1	65,600	22,424	7308	95,332
Module 2	25,263	22,424	9063	56,749
Module 3	25,263	22,424	5098	52,784
Module 4	25,263	22,424	6797	54,484
Module 5	111,901	28,150	7687	147,738
Module 6	132,245	28,150	8700	169,095
DGW	–	38,367	–	38,367

All prices are quoted in Singapore Dollars (SGD).
Note: DGW – double-glazed windows.

Table 10
Costs of semi-transparent BIPV systems after local government subsidy.

	Total capital cost	Actual cost (after 30% subsidy)	Additional cost (after deducting DGW)
Module 1	95,332	66,732	28,366
Module 2	56,749	46,712	1358
Module 3	52,784	36,949	−1418
Module 4	54,484	38,139	−228
Module 5	147,738	103,417	65,050
Module 6	169,095	118,367	80,000

16.7%), performance similar to the higher reduction in scenario 3 was observed. The modules that can breakeven obtain EPBT of 2.43–8.38 years and the increase as compared to base case was 223–257%. As for their EROEI, they ranged from 2.40 to 8.98, signifying a decrease of between 74% and 80%.

The results suggest that manufacturing the modules in a nearby country can greatly decrease the life cycle energy use by reducing the transport required. However, it is also important to note the electricity mix of the country, as some countries generate more GHG emissions per kWh of electricity which can result in displacement rather than an overall reduction in life cycle GHG emissions. In addition, the shadowing effects of surrounding buildings in an urban context, as reflected by the two levels of reduced SVF, can decrease the overall effectiveness of semi-transparent BIPV. All the modules and orientations investigated are able to achieve pay back within its life time with one-third shaded windows, but only half of them are able to do so when shading is increased to two-thirds of a window.

Although semi-transparent BIPV may perform better than common double-glazing, wider adoption of semi-transparent BIPV would also depend on the economic performance. This is investigated in the next section.

6. Life cycle economic performance of semi-transparent BIPV windows in Singapore

6.1. Analysis of long-term financial cost of BIPV systems relative to double-glazed windows

The initial cost of semi-transparent BIPV windows includes, the costs of module, supplying and fixing of aluminium framing, balance of system components, and the electrical work. The purchased costs of the modules are shown in Table 1 while quotations obtained from local glazing contractors to supply glazing and fixed aluminium framing and to install both single- and double- clear-glazed facades are shown in Table 8. A local photovoltaic system integrator estimated the costs of the remaining balance of systems and cost of electrical work (cabling, trunking, inverters, labour, etc.) to be SGD 2/Wp. The detailed breakdown of costs for the modules and double-glazed windows are shown in Table 9.

In a bid to promote environmentally-friendly green building technologies and clean energy adoption, the Singapore government funds up to 30% of the total capital cost of PV systems [36]. The additional cost of adopting semi-transparent BIPV systems as compared to a double-glazed wall, with the 30% subsidy deducted, is shown in Table 10. The 30% local subsidy, play an important role in lowering the additional costs of adopting a BIPV façade instead of the conventional double-glazed windows. The capital cost of modules 3 and 4, is less than that of a double-glazed window.

6.2. Payback period of investigated semi-transparent BIPV window systems

According to local contractors the maintenance of photovoltaic façade is similar to that of a conventional glazing and therefore was not considered. The NEB of adopting the semi-transparent BIPV systems, as opposed to double-glazed windows, were converted to electricity savings, which could be used as on-site generation to offset the operational costs of other building systems. The cost of electricity in Singapore at the beginning of 2013 was 0.281 SGD/kWh [37]. Only modules 1, 2, 5 and 6 with a higher cost relative to double-glazing were considered. The payback periods, estimated with the 30% government subsidy at constant electricity prices, and constant dollars approach are shown in Table 11. When the NEB is included, the initial additional cost of integrating PV modules 1 and 2 can be recovered with payback periods of 13.1–17.1 and 1.1–1.5 years, respectively. Modules 5 and 6 however, do not payback the additional investment during the 25-year life time, irrespective of their superior performance.

6.3. Sensitivity of results

For life cycle cost analysis, the cost of electricity is an important factor in determining its economic viability. The quarterly

fluctuations of Singapore's electricity prices over the past 8 years obtained from the sole provider of electricity [37], is shown in Table 12. These are used to formulate three scenarios for the sensitivity analysis of economic performance over the 25-year lifetime as follows:

- Scenario 1: Electricity prices increase based on the average increase rate on a year-on-year basis.
- Scenario 2: Electricity prices increase based on the minimum increase on a year-on-year basis.
- Scenario 3: Electricity prices increase based on the maximum increase on a year-on-year basis.

The analysis is limited to modules 1, 2, 5 and 6 only, as modules 3 and 4 are cheaper to install than double-glazed windows after the 30% government subsidy. The result of this economic sensitivity analysis is shown in Table 13. For module 1, the payback period decreases gradually from scenario 1 to 3 compared with the base case, while module 2 remained the same for all 3 scenarios, with the N/S orientation decreasing from 1.5 to 1.4 for scenario 3. This is due to the very low additional cost of installing it as a semi-transparent BIPV window façade. If module 5 is considered, with scenario 1, the cost of the module, can be recovered in 21.9 years with E/W orientation but not with the N/S orientation. For scenarios 2 and 3, both orientations achieved payback with the period required progressively decreased from scenarios 2 to 3. Module 6 has the worst performance in terms of payback period for all scenarios. For the E/W orientation, it achieves payback periods of 14.8–24.4 for all the variations. For N/S orientation, it can only payback for scenario 3, with a period of 17.4 years. The results indicate that the potential future increase in electricity prices can further increase the economic feasibility of semi-transparent BIPV windows.

7. BIPV decision-making tool

The main reason for lower uptake of building integrated solar energy systems today is the lack of technical knowledge among architects. The architects face issues due to the complexity of integrating photovoltaic systems during the building design.

Table 11
Economic payback period of the semi-transparent BIPV window systems.

	EW (years)	NS (years)
Module 1	13.1	17.1
Module 2	1.1	1.5
Module 5	#N/A	#N/A
Module 6	#N/A	#N/A

#N/A – BIPV system does not break even.

Table 12
History of Singapore's electricity tariffs.

Low Tension Tariff Unit: SGD ¢/kWh	Q1	Q2	Q3	Q4	Annual average
2005	17.9	17.2	19.6	21.0	18.9
2006	22.5	21.9	22.7	23.1	22.6
2007	21.4	20.2	21.9	22.9	21.6
2008	24.2	25.6	26.9	32.6	27.3
2009	24.5	19.3	20.7	23.2	21.9
2010	24.5	25.3	25.8	24.9	25.1
2011	25.8	27.4	29.2	28.9	27.8
2012	29.5	30.8	30.0	29.2	29.9
2013	28.1				28.1

Table 13
Payback periods of the six semi-transparent BIPV modules' life cycle cost for different scenarios.

	Base case (constant rate for 25 years)		Scenario 1 (year-on-year average increase of SGD 1.15 cents)		Scenario 2 (year-on-year min. increase of SGD 2.1 cents)		Scenario 3 (year-on-year max. increase of SGD 5.7 cents)	
	E/W	N/S	E/W	N/S	E/W	N/S	E/W	N/S
Module 1	13.1	17.1	10.9	13.5	9.8	12.0	7.7	9.2
Module 2	1.1	1.5	1.1	1.5	1.1	1.5	1.1	1.4
Module 5	#N/A	#N/A	21.9	#N/A	18.8	22.9	13.6	16.1
Module 6	#N/A	#N/A	24.4	#N/A	20.8	#N/A	14.8	17.4

All BIPV systems are assumed to receive 30% government subsidy as mentioned in Section 6.1.
#N/A – BIPV system does not break even.

One way to overcome this problem is to develop a decision tool to guide architects in the selection of photovoltaic materials. To refrain from exposing the architects (who are primarily concerned about design) to technicalities, there is a need for decision tools that inform them on the key performance aspects of semi-transparent BIPV window façades. Exact numbers and quantities derived from technical investigations should be "hidden" from the tool user and only a simple matrix for comparing key criteria should be presented. To promote optimum use of resources, the life cycle environmental and economic performance should be the basis of the decision tool. The results presented earlier in this paper were adopted to generate a tool for this purpose. The details of the tool and its development is discussed next.

7.1. Categories and criteria for selection matrix

The specific criteria for environmental performance included in the decision tool are: (1) total GHG emissions, (2) energy payback time (EPBT) and (3) energy return on energy investment (EROEI). Total GHG emissions, is an indication of implications on climate change. Both EPBT and EROEI are indicators as to whether the adoption of the specific renewable material or system is justifiable in terms of energy used versus energy generated.

Better environmental performance may not necessarily guarantee wider uptake of any technology. For building owners to adopt a certain technology or system, one of the key considerations is the cost. Hence, the decision should also take cost into consideration. Although capital cost is important, the payback period (if possible) can determine if it is worth investing in photovoltaic technologies. As such, both capital cost and payback time are included in the selection matrix.

A major drawback of the investigated semi-transparent BIPV modules is the very low visible light transmittance (VLT). This means limited visual connectivity with the exterior environment and daylighting, both of which are reasons why windows are preferred by occupants. Therefore, VLT is also incorporated into the selection matrix, so as to allow the tool users to make informed decisions on both performance and suitability.

7.2. Development of selection matrix

The tool includes the above data for the six PV modules and clear double-glazing, so as to allow comparisons of the relative performance when making the decision to adopt semi-transparent BIPV modules instead of conventional window glazing. Only the E/W orientation is included as this section serves to discuss the development of the selection matrix which is to be used as a guide. To plot the values on the selection matrix which is in the

form of a radar chart, the data were first normalized. In order to do so, the worst and the best values of a given indicator represent the range, and all data are shown as relative percentage values. For the VLT, the values are placed on a logarithmic scale (base 10) before obtaining the relative percentages. The normalized data for six modules and double glazing are shown in Table 14.

Fig. 3 shows a simplified version of the design tool with double glazing and two semi-transparent BIPV modules (modules 1 and 2). As seen in the design tool, the two modules display very different performance with respect to the categories. Module 1 has much better environmental performance, which is observed from the higher scores for GHG emissions, EPBT and EROEI. However, module 2′s economic performance is significantly better with higher values for both payback time and capital cost. This information allows architects or building designers to decide on the criteria that they like to pay more emphasis on. If there are regulations or company′s environmental policies governing the material usage, module 1 is likely to be chosen. In the case of cost limitations and a short term view on the building development project, module 2 may be chosen instead. In addition, with the VLT information included, the architect can also make an informed decision on the effect of the chosen module on daylighting. If environmental and economic performances do not indicate a clear "winner", the VLT can assist in making the decision as a higher VLT is likely to represent better occupants′ satisfaction.

8. Conclusions

The paper considered the life cycle performance of six commercially-available semi-transparent BIPV windows in commercial buildings in Singapore. The analysis considered the relative environmental and economic performance of semi-transparent BIPV windows compared with conventional clear double-glazed windows. The performance of semi-transparent BIPV windows not only included electricity generation capabilities but also the effects on the cooling load and artificial lighting requirement.

The results indicate that the major life cycle stages that require significant primary energy use are the manufacturing of photovoltaic modules and balance of systems. Cross-continental freight can be a major contributor to the total primary energy of a PV module. The energy payback time was less than two years while energy return on the investment could be as high as 35 times. Although purchasing photovoltaic components from a nearby country can greatly reduce the transport energy demand, it can also lead to increased GHG emissions, depending on the electricity mix of the country. Hence purchasing choices should encompass a holistic view. The shadows created by nearby buildings can decrease the overall efficiency of semi-transparent BIPV which should be considered during design stage. Detailed assessment would be necessary in the cases where 2/3 of windows are likely to be shaded.

Table 14
Modified data (only E/W) to include relative performances by considering the range of maximum and minimum values.

Category	Performance Indicator	Double-Glazing	East/West Orientation					
			Module 1	Module 2	Module 3	Module 4	Module 5	Module 6
Environmental Performance	GHG Emissions	63.38	100.00	0.00	28.96	16.63	41.34	34.33
	EPBT	80	100.00	22.94	43.53	25.62	62.91	0.00
	EROEI	80	100.00	7.30	22.94	9.24	44.69	0.00
Economic Performance	Capital Cost	98.26	63.42	96.59	100.00	98.54	18.36	0.00
	Payback Period	80	49.68	100.00	0.00	0.00	0.00	0.00
Occupant Preference	VLT	100.00	43.38	28.01	0.00	22.10	35.74	37.37

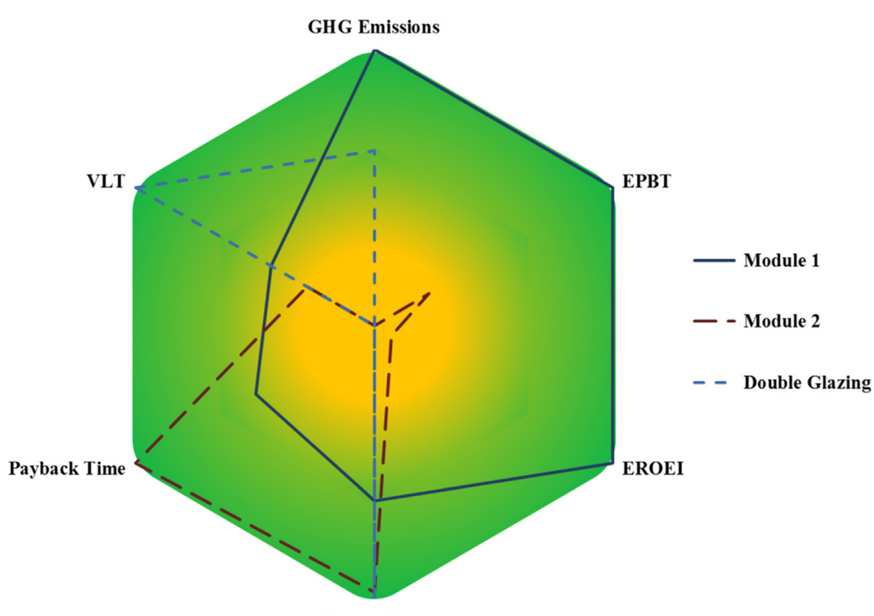

Fig. 3. Design tool in the form of a selection matrix showing two semi-transparent BIPV modules and double-glazing windows.

The government subsidy means that, certain PV modules are cheaper to install than conventional double-glazed windows, while the cost of the worst-performing module can also be recovered in 13 years. Any increase in the electricity prices improves the viability of semi-transparent photovoltaic systems. The BIPV design tool presented can aid integration of semi-transparent BIPV windows for optimum building performance in environmental and financial terms while ensuring occupant satisfaction.

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